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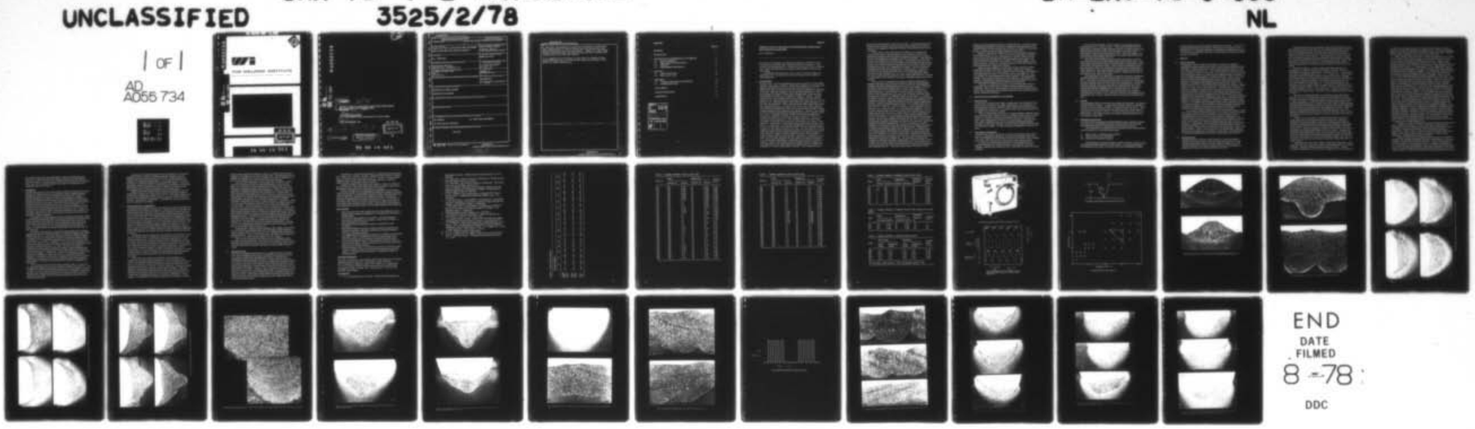

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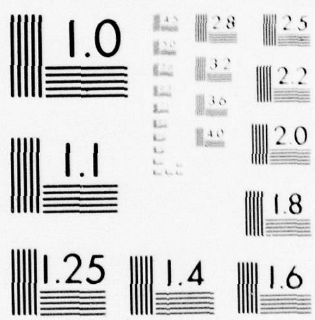

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In this work, the prospects of achieving an equiaxed or refined weld metal microstructure in ferritic steels using the pulsed wire feed spray MIG process have been investigated. Despite the large number of pulse conditions used, equiaxed solidification has in general been confined only to the weld root regions.

It is suggested that the process is most likely to succeed at high pulse frequencies, but is prevented from doing so by thermal inertia effects at these frequencies.

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By P.L. THREADGILL

In this work, the prospects of achieving an equiaxed or refined weld metal microstructure in ferritic steels using the pulsed wire feed spray – MIG process have been investigated. Despite the large number of pulse conditions used, equiaxed solidification has in general been confined only to the weld root regions.

It is suggested that the process is most likely to succeed at high pulse frequencies, but is prevented from doing so by thermal inertia effects at these frequencies.

1. BACKGROUND

In recent years, several investigations have been carried out at The Welding Institute in an attempt to develop a satisfactory technique for producing a fine equiaxed solidification structure in ferritic steel weld metal (1-4). It is believed that such a structure could result in improved mechanical properties of the weld, especially toughness, and in improved weldability by virtue of the increased resistance to solidification cracking which is found in welds which solidify in an equiaxed, as opposed to columnar, manner. Although techniques have been developed which have resulted in very fine equiaxed grains in Al by using artificial gas jet cooling on the surface (2,3), or by arc vibration (2,3), the factors which control weld metal grain refinement are, in fact, not well understood. This is demonstrated in other work carried out at The Welding Institute on 321 stainless steel, where early studies indicated that an equiaxed solidification structure could be obtained by using a complex modulated current during autogenous TIG welding (3). However, later studies by Lawson (5) have shown that the solidification structure in 'equiaxed' welds was, in fact, essentially columnar and that the observed equiaxed grain structure was caused by the repeated cycling through the $\delta \rightarrow \gamma$ phase transformation at high temperatures. The techniques which have been found successful on aluminium alloys only work on thin sheet, up to about 3.2mm thickness, and attempts to refine higher energy input welds with larger weld pools, e.g. submerged arc, using these techniques have proved quite unsuccessful, and other approaches have been taken. The only technique which has resulted in a fine equiaxed solidification structure in submerged arc welding of ferritic steels has been artificial inoculation of the weld pool using TiC or TiB_2, which can, under favourable welding conditions, lead to epitaxial growth of steel dendrites on the inoculant. The nuclei are soluble in molten steel, and it has been suggested that one condition for equiaxed nucleation, i.e. constitutional supercooling, is enhanced by the presence of titanium in solution. However, the benefits of grain refinement by this technique are more than offset by the large reduction in toughness which is caused by the formation of a coarse transformation structure, Ti(CN) precipitation and

films around cell boundaries, even in low S welds. It has been estimated that between 3 and 6 times the maximum titanium content which can be tolerated without loss of toughness is required to achieve a reasonable degree of grain refinement.

More recent work by Bäckerud and Edvardsson (6,7) in Sweden has shown similar results, and these authors have attempted to improve the mechanical properties while retaining the equiaxed structure by the addition of some cold welding wire in addition to the TiC grain refiner. They observed that for a given addition of TiC grain refiner, the equiaxed area of the weld (measured in transverse section) increased with increasing cold wire addition. However, even with the minimum requirement of grain refiner needed to give an equiaxed structure, poor toughness was obtained. The role of the grain refining agent is itself poorly understood, as additions of VC, which has a low lattice misfit with the nucleating solid at the solidifying temperature, produces no grain refinement (6). It is not at present understood whether this is due to some physical properties of the solid/liquid interface, or merely to rapid solution of the inoculant in the liquid, although the latter seems more probable.

Thus, to date, no completely satisfactory method of producing fine equiaxed weld metal grain structures in ferritic steels has been developed. Although a full understanding of the processes involved in weld solidification, particularly equiaxed weld solidification, has not been achieved, it is well established that certain conditions must be met in order to achieve an equiaxed structure. These include i) a plentiful supply of nuclei on which growth of the solidifying metal can occur, and ii) thermal conditions which will ensure the survival of a sufficient number of such nuclei. As artificial inoculation to provide a supply of such nuclei has been shown capable of giving an equiaxed structure, thus implying that suitable thermal conditions can be achieved, it should in principle be possible to achieve equiaxed solidification in ferritic steels using other species of nuclei. As no other artificial nuclei other than TiC, TiB_2, etc., are at present known, such refinement must of necessity rely on 'natural' nuclei, i.e. free fragmented dendrites. Work on Al alloys mentioned above has shown that these can be produced by cold gas jetting onto the weld pool surface, which produces a supply of dendrite fragments at the surface, or by arc vibration, which causes increased fluid motion in the weld pool, thereby breaking off dendrite tips at the solid/liquid interface, but that such techniques are viable only for thin (<3.2mm) sheet. An alternative method for disturbing the fluid flow of a weld pool, and thus the likelihood of dendrite fragmentation, is to use a modulated arc current. Changes in arc current will alter the magnitude of the Lorentz forces which are largely responsible for fluid motion in the weld pool. Modulated arc currents have proved successful in grain refinement in 321 stainless steel (3,5) using autogenous TIG welding, but although this refinement has been shown to be induced by solid state transformation rather than solidification, convincing evidence of the ability of the process to influence the solidification behaviour of the weld was obtained (5). One advantage of modulated arc welding as a technique for dendrite fragmentation, in theory at least, is that it should still be fairly effective in larger weld pools, as the intense fluid motion in the weld pool caused by the modulation is likely to be transmitted to the solidifying interface. The thermal pulse effects are likely to be less

effective than the mechanical effects in a large weld pool. It therefore seems a reasonable development of this work to extend the modulated current work to ferritic steels, and the present work is based on a proposal (8) to study the effects of modulated current in MIG welding of ferritic steels.

Recently, a pulsed wire feed spray MIG process has been developed at The Welding Institute (10,11). This process has the advantage of providing close control of the weld pool and increased arc stability, and its use can result in significant advantages for root pass welding where access to the back of the joint is restricted or not possible, e.g. in pipe welding. In the present situation, the process is attractive because of the wide variations in pulse characteristics which can be achieved.

Metal inert gas welding is also attractive in that it has the broadest applicability for high productivity, high quality welding of all classes of structural materials. It is more productive than TIG welding, and capable of wider application than other arc processes such as submerged arc. It is also suitable for both mechanised and manual operation, and for positional welding. In the present programme of work therefore, an investigation is made into the feasibility of using pulsed wire feed MIG welding as a route to achieving equiaxed solidification and refined microstructures.

This work is divided into two parts, the first being a short series of preliminary bead on plate tests to establish optimum conditions to grain refinement, followed by a more intensive study using more realistic bead in groove tests to investigate the relationship between various pulse parameters and the solidification structure.

2. APPARATUS AND EXPERIMENTAL TECHNIQUES

2.1. General equipment

A transformer/rectifier power supply, nominal open circuit voltage 60V and 1000A current rating with a flat output characteristic, was used to drive a Welding Institute transistor regulator (500A rating) which provided the peak and background current levels. A constant current output characteristic from the regulator was chosen for stability.

The wire feed system was based on a 150mm diameter multigrip capstan wheel driven through a reduction train by a printed-armature motor of rapid response. The motor itself was electronically driven at the high and low levels, using regenerative feedback for the speed control. The tests were made using a mechanised rig, with a commercial welding gun installed vertically, in which the workpiece was traversed horizontally beneath the gun on a motorised carriage. An argon 5% oxygen shielding gas was used for all welds.

2.2. High response wire feed system

A standard wire feeder, powered by a motor typical of those used commercially, is unsuitable for pulsing the wire feed at frequencies greater than ~2Hz, due to high inertia in the motor and wire drive systems, and to slipping of the pinch rolls at the points of contact when being switched rapidly.

In order to overcome these limitations, The Welding Institute has recently developed a low inertia wire feed system together with a high response, electronically-controlled motor, specifically developed for pulsed operation.

The wire drive assembly, which is based on The Welding Institute's multigrip system (9), is shown in Fig. 1. The essential features were the positive feed, obtained by using a relatively long arc of tractive contact (up to 50mm) between the wire and the 150mm diameter drive wheel, and the relatively low inertia of the motor and drive train. Slip-free feeding, even when rapidly accelerating and decelerating, was readily achieved even with pinch forces too low to deform the wire.

The 175W printed-armature motor used was chosen for its relatively low armature inertia, and comparatively high torque-to-inertia ratio. The motor speed was governed by the back emf generated, which itself is directly proportional to the armature speed. Using a closed-loop feedback system, the motor power supply was commanded to overdrive while accelerating to a higher speed level, and to apply dynamic braking during de-acceleration to a lower speed level. This gives a better frequency response than the natural performance of the motor would permit.

The capabilities of the apparatus are demonstrated by the oscillograms obtained by Street and Lucas in a previous study (10), which are shown in Fig. 2. From these, the almost perfect square wave form of the current and the rapid response of the wire feed system can be appreciated. The limiting frequency response of the wire feed system is approximately 8Hz, above which the inherently exponential rates of rise and decay have been found to prevent full amplitude modulation of the wire feed speed (10). Partial compensation for this inertial lag in wire feed system can be obtained by switching the drive motor 0.01 to 0.02msec in advance of the welding current, allowing the wire to reach a significant speed by the onset of the high current level.

2.3. Materials

The preliminary welds were made on 6mm bright mild steel plate, the analysis of which is given in Table 1. A commercial 1mm dia C-Mn wire, supplied to BS 2901: 1970 was used for all welds. Its analysis is given in Table 1. Bead in groove tests were performed on 19mm mild steel plate, and the relevant composition is also given in Table 1. Details of the groove preparation, are given in Fig. 3. The same wire batch was used for the bead in groove welds as the bead on plate welds.

2.4. Metallographic examinations

All welds made were examined metallographically using a transverse section of the weld, and a longitudinal section in a plane normal to the plate plane. The longitudinal section was taken along the centre line of the weld.

All weld sections were polished to 1μ and examined both macroscopically and microscopically to establish the following:

i) extent, if any, of equiaxed grain structure
ii) extent and type of any weld defects
iii) unusual microstructural features.

Each specimen was examined using two etches, the first, 2% nital to show the transformed microstructure, and the second, a chloride based dendrite etch (hydrated $FeCl_3$ 13gms, $CuCl_2$ 1gm, HCl 13mls, distilled H_2O 300mls,

C_2H_5OH 250mls) to reveal the original solidification structure. This etch acts by preferential deposition of copper on areas lean in alloy content, such as dendrite cores. It is therefore capable of revealing the solidification structure of a ferritic steel weld after solid state transformations, and in fact even after postweld normalising.

3. RESULTS

3.1. Bead on plate welds

A preliminary series of bead on plate welds was made in an attempt to establish those pulse conditions most likely to confer grain refinement in the weld metal. In this series of tests, the arc pulse currents were set at 300A, with a background current of 25A. The traverse speed was adjusted to give a constant mean arc energy of 0.38kJ/mm. The small weld pool size was thought to be advantageous since it was felt that grain refinement was more likely to occur by dendrite fragmentation in a smaller weld pool. Figure 4 shows the matrix of pulse times/background times studied, which were determined primarily by the physical characteristics of the pulsed wire feed control apparatus, and details of the welding conditions are given in Table 2. The diagram shows the area in which most grain refinement was observed, namely a pulse of ~0.2sec, with 0.3sec background. Examination of a weld made under such conditions, shown in Fig. 5a, showed that the finger at the root of the weld in particular contained a very fine equiaxed prior austenite grain structure which was shown by etching in the chloride dendrite etch to have originated from an equiaxed solidification mode, Fig. 6. The pulse parameters appeared to be critical, since surrounding points on the matrix showed little tendency for this equiaxed structure. A typical unrefined structure is shown in Fig. 5b. No condition could be identified on the matrix which gave an overall equiaxed structure, and in particular it seemed impossible to prevent the formation of a columnar grain structure growing into the weld from the region of fusion boundary between the root and toes of the welds.

In an attempt to induce refinement by solid state transformations, welds were made in which the pulse/background ratio was kept as small as possible, with background times as long as possible, in the anticipation that the solidified regions of the weld might cool sufficiently to undergo the $\delta \rightarrow \gamma$ transformation or even the $\gamma \rightarrow \alpha$ transition before being reheated by the next pulse, with the hope that multiple transformations may refine the microstructure. Unfortunately, both small pulse/background ratios and long background times tended to lead to arc instability and unsatisfactory welds, as large droplets of molten metal formed on the wire during long (>0.5sec) background periods. However, even with the most promising pulse conditions which were compatible with arc stability (0.1sec pulse, 0.4sec background) no evidence for refinement by solid state transformation was observed.

3.2. Bead on plate tests

Although the bead on plate test welds had failed to produce an entirely equiaxed weld microstructure, they had shown that the pulsed wire feed system could produce at least a partially refined structure, and it was therefore decided on this basis to proceed with the main investigation on preparations which more closely resembled real welds.

As the grooved plate was substantially thicker than the bright mild steel plate used for the bead on plate test, it was obvious that thick plate would act as a more efficient heat sink. This effect was compounded by the groove design, which allowed heat flow from the weld to occur in a much wider arc than from the bead on plate deposits. Thus preliminary tests were carried out to establish the minimum heat input required to obtain adequate 'wetting in' of the pool and freedom from lack of fusion type defects etc. These trials showed that a nominal arc energy of 1.5kJ/mm based on mean currents would be required and most of the tests were carried out at this level of arc energy.

In the first instance, a matrix of pulse and background times was investigated at a constant arc energy of nominally 1.5kJ/mm, which was maintained by varying the welding speed. Pulse times of 0.1, 0.2 and 0.3sec were used with background times of 0.1, 0.2, 0.3 and 0.4sec. None of these conditions produced an entirely equiaxed transformed structure, although fine equiaxed regions were observed in the fingers at the root of the welds for all 0.2 and 0.3sec pulse conditions. The extent of these regions was not obviously dependent on background time. Limited equiaxed regions were observed in the root regions of the 0.1sec pulse welds, but the grain size was in general somewhat coarser, and the 'finger' at the root of the weld was not as clearly defined as in the 0.2 and 0.3sec welds. Transverse sections of these welds are shown in Fig.7, and details of the welding conditions are given in Table 3.

For any given background period, it was clear that the only effect of pulse time is to give increased finger penetration with higher pulse times, although the extent of equiaxed grain structure does not seem to vary between 0.2 and 0.3sec pulses. No apparent effect on transformed structure of increasing background time for a constant pulse time could be readily identified. Examination of the solidification structures of these welds did not indicate any pronounced effect of pulse parameters on solidification structure. Figure 8 shows a typical example etched in the chloride dendrite etch, where fine equiaxed solidification structures in the root of the welds give way to coarser equiaxed structures and then columnar structures as the toes of the weld are approached.

However, it was noted that an equiaxed solidification structure was usually associated with an equiaxed transformed structure, with finer solidification structures leading to finer prior austenite grain structures. Since these results suggest that the degree of grain refinement could depend on the weld pool shape, in particular the finger depth, further trials were carried out at 1.5kJ/mm using pulse currents of 350 and 400A, in the hope of obtaining proportionally larger fingers in the root regions. Although this resulted in some modification to the transverse section, this was only slight, and no real improvement in the extent of the equiaxed regions was obtained. In fact the 400A current gave welds of unsatisfactory quality, with very poor wetting-in at the weld toes, particularly at high pulse/background ratios, as shown in Fig.9.

Subsequent tests were tried at higher overall pulse frequencies, using pulse times of 0.025, 0.050 and 0.075sec with background times of 0.025 and 0.050sec. Details of welding conditions are given in Table 3. Recent theoretical calculations by Lawson (12) have suggested that a pulse frequency

of ~15Hz is the optimum value for creating weld pool turbulence, and thus hopefully creating a plentiful supply of dendritic nuclei. The results obtained, shown in Fig. 10 did not provide any evidence to support this theory, although effective pulse frequencies in the range 8 → 20Hz were used.

Other work by Lawson (5) on pulsed current TIG welding of 321 stainless steel has shown that by superimposing a current modulation onto the pulse, it was possible to influence the solidification structure. Lawson's work however used very long background periods of up to 4sec, which although perfectly feasible for TIG welding, is impractical for MIG welding for reasons outlined earlier (section 3.1). Nevertheless, it was thought that in view of the failure of more straightforward means of pulsing in achieving refinement, investigation of this method was justified. As a comparison, welds were first made with the very low frequency pulses similar to those used by Lawson, but without the superimposed high frequency modulation. Pulse times of 0.5, 1.0 and 2.0sec were used with a background pulse time of 0.5sec, which was the maximum compatible with the arc stability. Apart from the obvious effects of the pulsing on the macrostructure visible in Fig. 11, no greater degree of refinement was observed than that achieved by other methods. Pulse current modulations of 10, 20 and 50Hz were then superimposed on the pulse cycle to give a waveform as shown in Fig. 12. Details of these welds are presented in Table 4. Figure 13 shows the effect of a 10, 25, and 50Hz modulation on the microstructure. It is immediately obvious by comparing Fig. 11 and Fig. 13 that the modulation decreases the penetration of the root, and that this effect is increased as the modulation frequency decreases from 50 to 10Hz. As the modulation had a pulse/background time ratio of one, and the traverse speed remained constant, there was an effective drop in arc energy compared to unmodulated welds, but the arc energy should be the same for these particular welds regardless of modulation frequency. This therefore suggests that the arc energy transfer efficiency is dependent on the modulation frequency. However, despite the variations in weld pool shape apparently induced by changing the modulation frequency, again no extensive refinement occurred. The weld in Fig. 13 with 10Hz modulation did show an apparently extensively equiaxed structure, but examination of a transverse section shows this to be confined purely to the root and throat regions. Apart from this, the equiaxed structure is still comparatively coarse, with a mean grain size of approximately 40μ.

The effect of current modulation alone without pulsed wire feed is not so clear. Comparison of Fig. 14a, b and c which show a current of 275A modulated at 100, 50 and 25Hz to 50A demonstrates that the effect on weld pool shape is somewhat unpredictable, with an apparent maximum in penetration at ~50Hz. Again, variations in current modulation alone do not appear to give any real improvement in the degree or extent of grain refinement. Welding details are given in Table 5.

A further series of tests investigated briefly the effect of modulation frequency and the pulse/background time ratios during the pulse on the weld structure, and the details are given in Table 6. Using a basic pattern of a 0.2sec pulse with a 0.3sec background period, modulation frequencies of 50, 25 and 10Hz were superimposed. The results can be seen in Fig. 15 from which it is apparent that modulation frequency has little effect on the transformed structure. Similarly variations in the pulse/background time ratio of

the modulated pulse have been investigated. Pulse time/background time ratios of 1, 2 and 5 have been used, but again there is very little effect on the microstructure. The cross sectional area clearly increases with increase in the ratio, due to the higher effective heat inputs of the high pulse time/background time ratios (Fig. 16).

4. DISCUSSION

It would seem from the wide variety of pulse conditions employed that current pulsing and modulation alone is not sufficient to induce extensive equiaxed solidification structures over the ranges studied during MIG welding. A similar conclusion was reached by Lawson on submerged arc welding (4), although the pulsing was not so severe in that instantaneous current changes between high and low levels were not possible with the power source which he employed, and current transients took up to a second to stabilise. It is probable therefore that both the thermal and mechanical disturbances in the present work were substantially greater than in Lawson's work. Again, in agreement with Lawson's results, equiaxed solidification was confined to the root finger regions of the weld, and its extent was found to be more or less insensitive to pulse parameters.

In principle, it would be expected that the current thermal pulses caused by the thermal pulsing would break up columnar structures by the intermittent partial remelting of the dendrites, and the fragments broken off would be redistributed around the weld pool by the intense fluid motion which would exist. It is clear that this has not in general happened in the expected manner, as little evidence of equiaxed solidification away from the root has been observed.

The shape of the weld pool, in particular the presence of a root finger, suggests that the thermal pulse is effective in melting off dendrite tips mainly directly under the arc, and in other regions of the pool insufficient changes in thermal energy are transmitted by the pulse to induce an adequate degree of remelting, i.e. the degree of superheat in the weld metal away from the region under the arc is low. Although it is clear from sections etched in the chloride base dendrite etch that pulsing has interrupted the solidification in the tail and toe regions of the pool, e.g. Fig. 8, the lack of any equiaxed solidification in these regions suggests that either dendrite fragments have not been formed in these regions, or have not been swept here by fluid flow from the root regions. Alternatively, if they have momentarily existed, then the thermal conditions in regions are such as to render then unstable or ineffective. Certainly it is clear that, in regions remote from the weld root, columnar grains appear to have grown through the pulse bands apparently uninterrupted. This effect was also reported by Lawson in submerged arc weld metal.

From sections of the weld etched in the dendrite etch, it is clear that the current pulsing produces strong mechanical pulsing in the weld pool. This is sufficient to produce pronounced serrations on the weld surface, as shown in Figs 6, 11 and 13 and also to push molten metal a considerable distance up the steep sides of the edge preparation in low frequency welds. However, it seems from the results that the mechanical pulsing has little effect on the solidification structure.

Assuming that dendrite fragments did exist momentarily, the thermal conditions which are required to stabilise dendrite fragments near the solidifying interface and permit them to grow are a shallow temperature gradient and constitutional supercooling. It is unlikely that either of these conditions are sufficiently fulfilled in the present experiments. Lawson (4) attempted to improve the degree of constitutional supercooling by using highly alloyed filler wire in pulsed submerged arc welding, but with no success, thus suggesting that the thermal gradients were too steep anyway.

Another phenomenon which has been observed consistently is that the solidification structure was always finest at the weld root fusion boundary, and steadily coarsened with distance away from it. This implies quite clearly that the stable solidification nucleus density is greatest close to the fusion boundary, and decreases with distance. This effect has not been reported as such for submerged arc welding.

4.1. Proposed mechanism for solidification

The arguments presented above allow a mechanism for the weld solidification during pulsed MIG welding to be proposed. During the pulse, most of the arc energy transferred to the pool is used to melt parent plate directly under the arc, and the electromagnetic forces generated push the molten metal to the sides and tail of the pool. The evidence suggests that this backwash of molten metal has very little superheat, since many small lack-of-fusion defects towards the weld toe were observed, and the backwash which reached the tail of the pool solidified immediately to form a pronounced surface serration. The backwash, although temporarily halting solidification processes, does not appear to melt back the growing columnar dendrites sufficiently to create a large enough population of dendrite fragments to induce equiaxed solidification. If dendrite fragments were broken off by the backwash, then clearly they did not survive.

Immediately after the current has been switched to the low level, only a pilot arc remains which is insufficient to maintain a molten weld pool, but supplies sufficient heat to reduce thermal gradients under the arc. Thus favourable conditions for equiaxed solidification are established in the weld root finger where sufficient quantities of dendrite fragments to act as nuclei have remained from the last stages of the high current pulse. Away from the root, where insufficient numbers of dendrite fragments exist, further solidification occurs by epitaxial growth on the partially remelted or arrested columnar grains, which are already correctly orientated for rapid growth, and thus provide the most favourable sites for further solidification processes.

This model can account for the apparent lack of dependence of solidification structure on pulse parameters. During the high current portion, any dendrite fragments broken off in the root regions will of course have a very short life, as they will either be completely remelted by the superheat which exists in the root, or will be swept away, and again probably melted by the much lower superheat which exists elsewhere. Only those fragments formed immediately prior to the high to low current switch can stand any real chances of survival, and so the actual pulse time itself is a comparatively meaningless parameter in terms of solidification. In this respect, it is significant to note that modulated pulses in general produced

slightly greater degrees of refinement, which is consistent with the greater frequency of the high to low current switching event. The background time is probably only significant if it is short enough to interrupt the solidification of the dendrite fragment rich regions close to the fusion boundary.

From the above arguments, it seems likely that the chances of grain refinement would be increased by using high frequency current pulsing. Since it is not feasible to use the pulsed wire feed MIG process to its best advantage at frequencies greater than about 8Hz, at which it is known to be ineffective in producing extensive grain refinement, a series of welds was made using modulated current only at frequencies of 25, 50 and 100Hz, all with a unit pulse to background time ratio, and using a continuous wire feed. Unfortunately, the weld pool characteristics were completely changed by this high frequency pulsing (Fig. 14), so that the characteristic root finger completely disappeared particularly at high frequencies. Furthermore, there was none of the characteristic backwash up the sides of the edge preparation at 50 and 100Hz. The high frequency pulsing was therefore ineffective, probably due to thermal inertia effects, where the pulses were so short that there was insufficient time for the build up of a thermal mass. Furthermore, high frequency pulsing is likely to increase the intense fluid motion, and thus give greater fluid flow and reduce temperature differentials between pulse and background periods. It is therefore not surprising that conditions for grain refinement were not achieved. It is clear from this work that weld pool shape has an important effect on solidification processes, and that the presence of a root finger is essential for equiaxed solidification. Previous work on TIG welding of mild steel has shown that such a root finger is only formed at currents of 200A and above (13).

Assuming that a similar situation applies in MIG welding, this provides an explanation for the disappearance of the root finger at high frequencies, where it appears that the mean current is more significant than the peak and background levels. Thus, in the present case, the mean current would be of the order of 175A, below the level required to form a finger.

The weld pool shape therefore appears to exert an influence on the possibility of grain refinement. The formation of a finger in the weld root promoted grain refinement within the crater, and the present results indicate that grain refinement by equiaxed solidification is not possible outside the crater.

4.2. Possible future work

This work has demonstrated that the use of a single pulsed arc on ferritic steel causes insufficient interruption of solidification processes to lead to true equiaxed solidification throughout the weld pool, and that such a solidification mode is generally confined to a small area in the weld root. The results of the present study give little confidence that variations in pulse parameters alone will be able to induce totally equiaxed refinement, since it appears that generation of suitable nuclei occurs only directly under the arc, and requires a root finger, and few, if any, of the nuclei survive to act at the sides or tail of the pool. A possible solution might be to investigate pulsed multi-arc systems, wherein the original MIG pool is partially remelted by a second TIG torch, which could have the effect of providing more nuclei near the tail of the pool, and perhaps refining parts of the original MIG pool by solid state transformations.

Alternatively, a weaved and pulsed MIG arc might again distribute nuclei over a wider area, although, as before, refinement could possibly be confined only to the regions close to the fusion boundary. However, weaving would be expected to give a lower depth/width ratio in the weld pool, so that the relative amount of refinement could be modified.

Another possibility which might prove fruitful is a cold wire addition to the tail of the pool, which would help reduce thermal gradients, and improve the stability of any nuclei which might exist in this region.

The most fruitful route to achieving grain refinement by this process would almost certainly be to investigate the solidification process of materials such as aluminium, or possibly fully austenitic stainless steel where previous work has shown that pulsed current techniques can exert a considerable influence on solidification processes, at least in thin plate. On the basis of the present work, there seems to be little prospect of using this process to grain refine welds in ferritic steels without a much greater understanding of the solidification processes involved, and the fluid properties of the weld pool.

CONCLUSIONS

1. Pulsed wire feed spray MIG welding has been found ineffective in producing extensive equiaxed solidification or transformation structures in the weld metal.
2. The weld pool shape appears to be critical. All grain refinement observed was confined to the root finger. Where this was absent, no grain refinement was observed.
3. The degree of grain refinement achieved is insensitive to pulse parameters.
4. Equiaxed solidification structures usually resulted in equiaxed transformation structures, with finer solidification structures leading to finer prior austenite structures.
5. It is suggested that high frequency pulsing is more likely to lead to grain refinement, since it is believed that the more frequent high to low current switching event will stabilise momentarily suitable nuclei.
6. The possible beneficial effects of high frequency pulsing is limited by thermal inertia effects, and the dominance of mean current rather than peak current at high frequencies.
7. From the present study, it is believed that pulsed wire feed spray MIG welding is unlikely to lead to weld metal grain refinement in ferritic steels. It is probable that the potential for refinement is higher in aluminium alloys.

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The author is indebted to many Institute staff for their help and co-operation during the course of this work. In particular, thanks are due to Mr R. Chapman for making the welds, and to Messrs G. E. Regelous and P.O. Kerr and their staffs for specimen preparation and metallography. Discussions with Mr N. Bailey, Mr J. Street and Dr W. Lucas are also gratefully acknowledged.

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Table 1. Plate and wire analysis

	Element weight %																
	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Al	B	Pb	Sn	Co
Bright mild steel	0.15	0.028	0.009	0.02	0.78	0.01	<0.01	<0.01	<0.01	0.04	<0.005	<0.01	<0.005	<0.001	<0.01	<0.01	<0.01
19mm mild steel	0.22	0.033	0.017	0.02	0.90	0.07	0.03	<0.01	<0.01	0.05	<0.005	<0.01	0.005	<0.001	<0.01	<0.01	0.01
1mm wire	0.09	0.022	0.011	0.83	1.44	0.05	0.06	0.01	<0.01	0.62	<0.005	0.01	<0.005	<0.001	<0.01	0.03	0.01

Table 2. Welding conditions, bead on plate tests

Weld no.	Pulse		Background		Traverse m/min
	Current (A)	Time(s)	Current (A)	Time(s)	
181	300	0.075	25	0.075	0.390
182	300	0.075	25	0.050	0.465
183	300	0.075	25	0.025	0.560
184	300	0.050	25	0.075	0.335
185	300	0.050	25	0.050	0.400
186	300	0.050	25	0.025	0.500
187	300	0.025	25	0.025	0.360
188	300	0.2	25	0.075	0.150
189	300	0.2	25	0.065	0.175
190	300	0.2	25	0.05	0.210
191	300	0.125	25	0.075	0.390
192	300	0.125	25	0.1	0.350
193	300	0.125	25	0.125	0.325
194	300	0.1	25	0.125	0.290
195	300	0.1	25	0.1	0.325
196	300	0.1	25	0.075	0.370
219	300	0.1	25	0.2	0.50
220	300	0.1	25	0.25	0.44
221	300	0.1	25	0.3	0.39
222	300	0.15	25	0.2	0.63
223	300	0.15	25	0.25	0.56
224	300	0.15	25	0.3	0.50
225	300	0.2	25	0.2	0.72
226	300	0.2	25	0.25	0.65
227	300	0.2	25	0.3	0.59
228	300	0.3	25	0.3	0.72
229	300	0.3	25	0.35	0.67
230	300	0.3	25	0.4	0.63
231	300	0.25	25	0.25	0.70
232	300	0.25	25	0.3	0.64
233	300	0.25	25	0.35	0.59
234	300	0.25	25	0.4	0.55
235	300	0.2	25	0.35	0.56
236	300	0.2	25	0.4	0.52
237	300	0.15	25	0.35	0.48

Table 3. Welding conditions, bead in groove tests

Weld no.	Pulse		Background		Traverse m/min
	Current (A)	Time(s)	Current (A)	Time(s)	
267	280	0.1	44	0.1	0.198
268	280	0.1	44	0.2	0.144
269	280	0.1	44	0.3	0.120
270	280	0.1	44	0.4	0.102
271	280	0.2	44	0.1	0.258
272	280	0.2	44	0.2	0.198
273	280	0.2	44	0.3	0.166
274	280	0.2	44	0.4	0.138
275	280	0.3	44	0.1	0.276
276	280	0.3	44	0.2	0.228
277	280	0.3	44	0.3	0.198
278	280	0.3	44	0.4	0.174
285	300	0.025	50	0.025	0.210
286	300	0.025	50	0.050	0.150
287	300	0.05	50	0.025	0.276
288	300	0.05	50	0.050	0.219
289	300	0.075	50	0.025	0.306
290	300	0.075	50	0.050	0.240
291	350	0.1	50	0.1	0.265
292	350	0.1	50	0.2	0.185
293	350	0.1	50	0.3	0.150
294	350	0.1	50	0.4	0.130
295	400	0.1	50	0.1	0.320
296	400	0.1	50	0.2	0.230
297	400	0.1	50	0.3	0.180
298	400	0.1	50	0.4	0.150
304	275	0.5	50	0.5	0.185
305	275	1.0	50	0.5	0.240
306	275	2.0	50	0.5	0.300

Table 4. Welding conditions, modulated pulsed current tests

Weld	Pulse		Background		Modulation frequency, Hz	Traverse speed, m/min
	Time (s)	Current (A)	Time (s)	Current (A)		
307	0.5	275	0.5	50	50	0.185
308	0.5	275	0.5	50	20	0.185
309	1	275	0.5	50	50	0.240
310	1	275	0.5	50	20	0.240
311	1	275	0.5	50	10	0.240
312	2	275	0.5	50	50	0.300
313	2	275	0.5	50	20	0.300
314	2	275	0.5	50	10	0.300

Table 5. Welding conditions, modulated current tests (constant wire feed speed)

Weld	Pulse		Background		Modulation frequency, Hz	Traverse, m/min
	Current (A)	Time (s)	Current (A)	Time (s)		
315	275	0.020	50	0.020	25	0.2
316	275	0.010	50	0.010	50	0.2
317	275	0.005	50	0.005	100	0.2

Table 6. Welding conditions, modulated pulsed current

Weld	Major pulse		Modulation		Traverse speed, m/min
	Pulse time (s)	Background time (s)	Pulse time (s)	Background time (s)	
299	0.2	0.3	0.01	0.01	0.166
300	0.18	0.32	0.02	0.02	0.166
301	0.25	0.25	0.05	0.05	0.166
302	0.2	0.3	0.02	0.01	0.166
303	0.23	0.27	0.05	0.01	0.166

For all welds, pulse current = 280A, background current = 50A

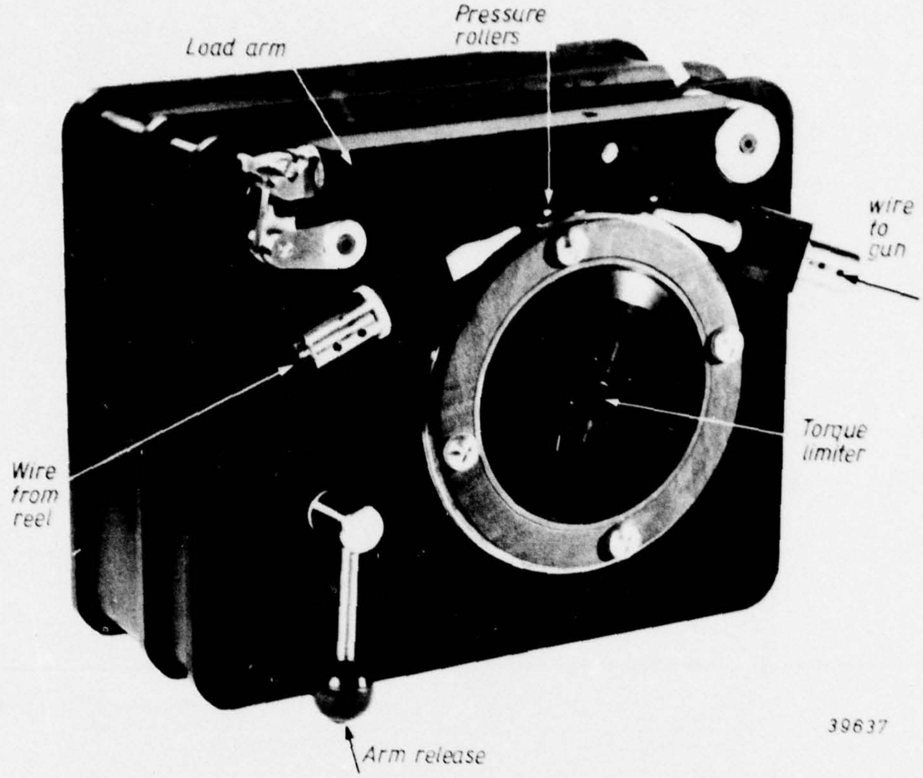


Fig.1. Multigrip wire feeder with 150mm diameter drive wheel, half full size.

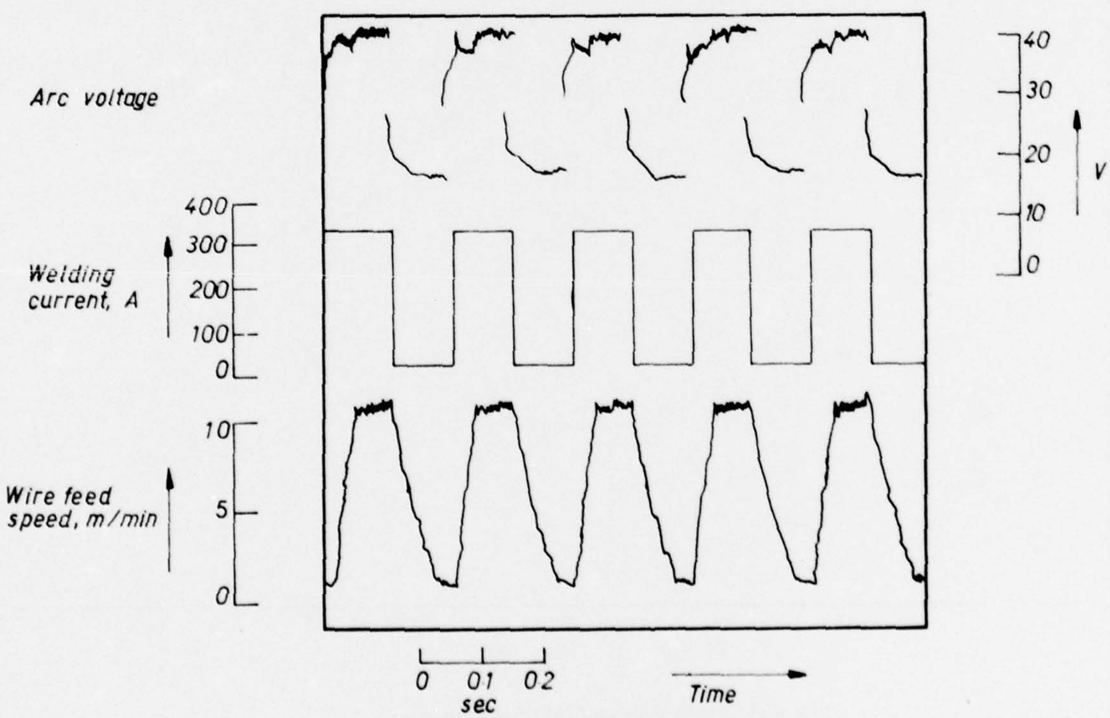


Fig.2. Typical oscillogram for pulsed wire feed MIG arc using transistor power supply (constant current mode) (from Street & Lucas, Ref.10).

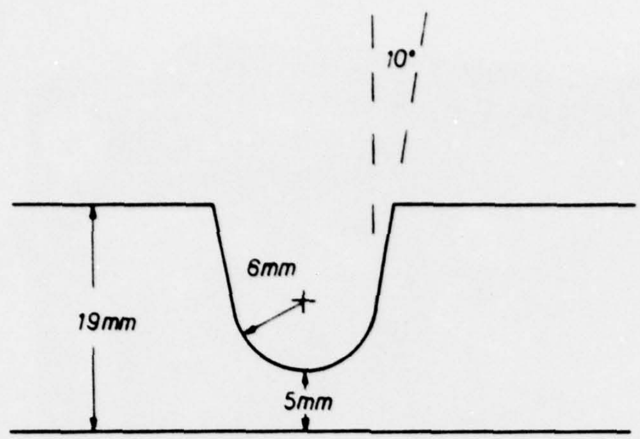


Fig.3. Diagram of edge preparation for bead in groove tests (not to scale).

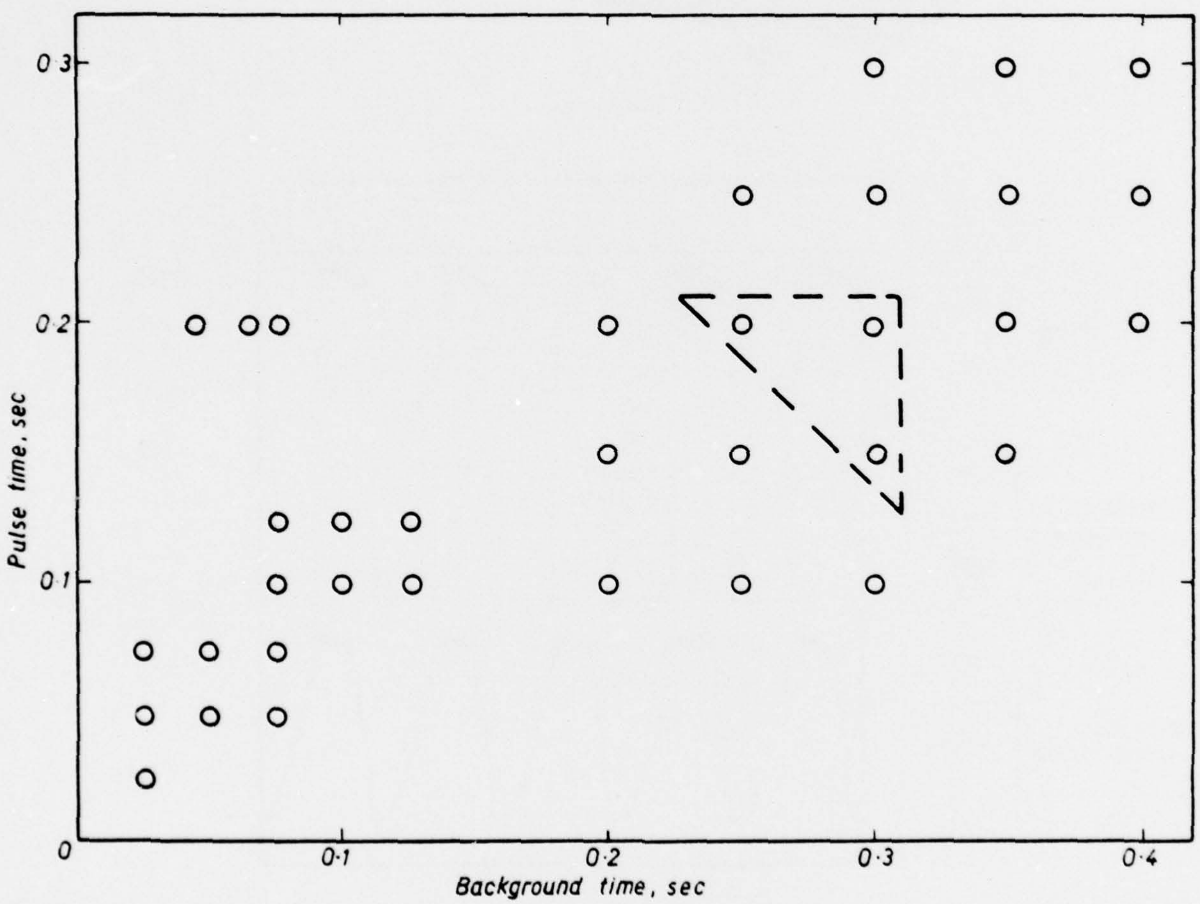
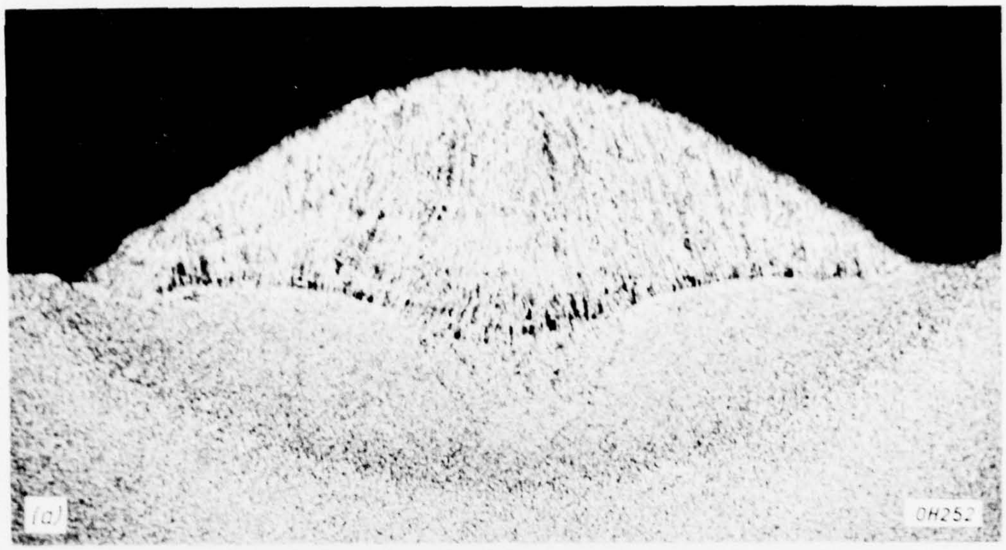


Fig.4. Pulse conditions for bead on plate tests.



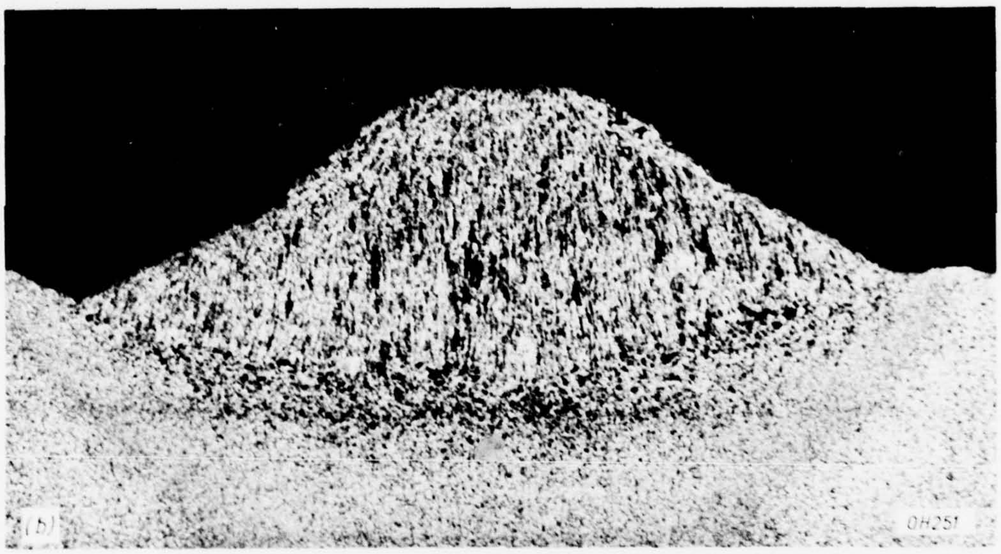


Fig.5. Transverse microsections of bead on plate welds: a) weld 227, pulse 0.2sec, background 0.3sec, note extensive refinement in finger. x 15; b) weld 196, pulse 0.1sec, background 0.075sec, no refinement.

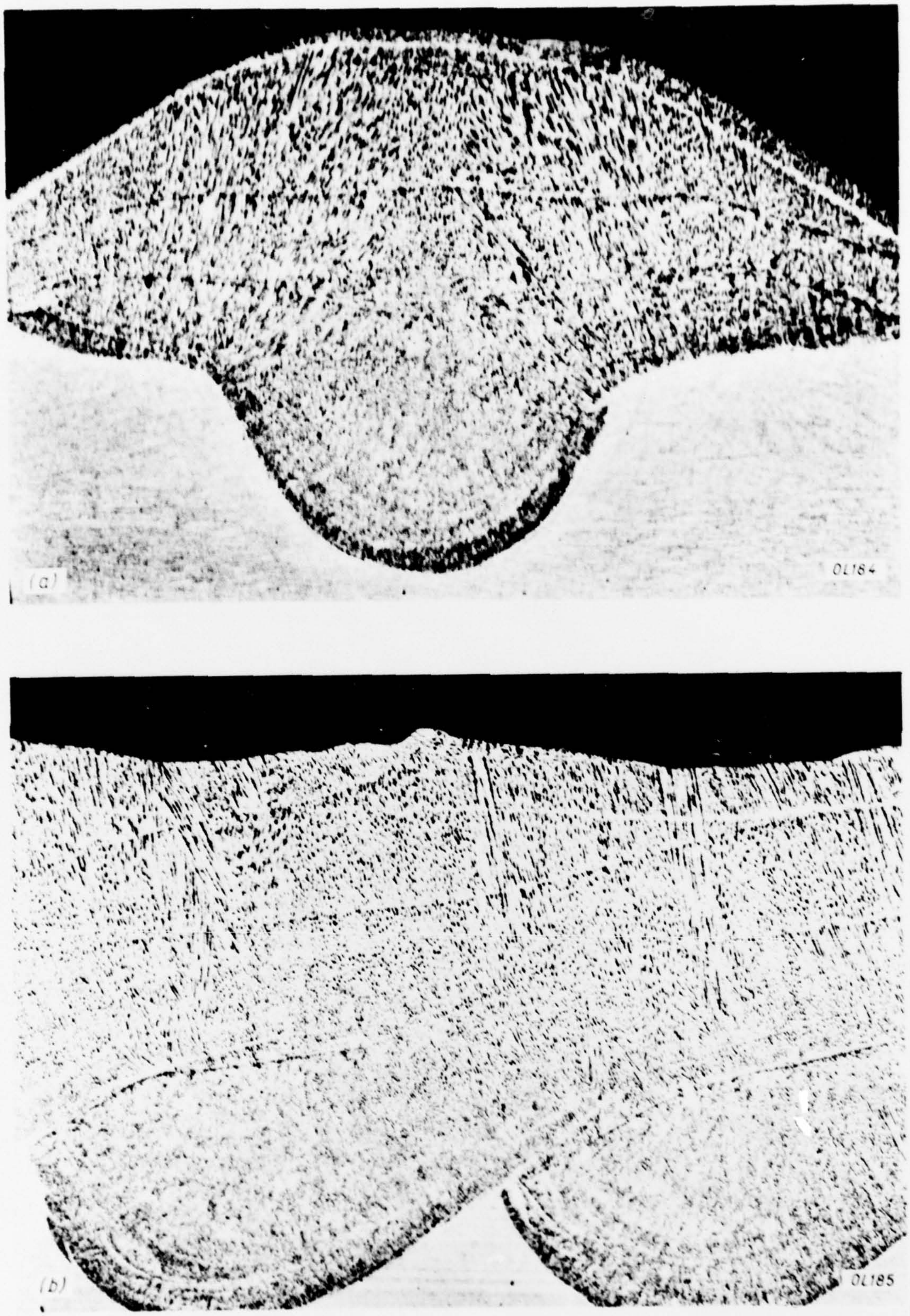


Fig.6. As Fig.5a etched in dendrite etch x 25: a) Transverse section; b) longitudinal section

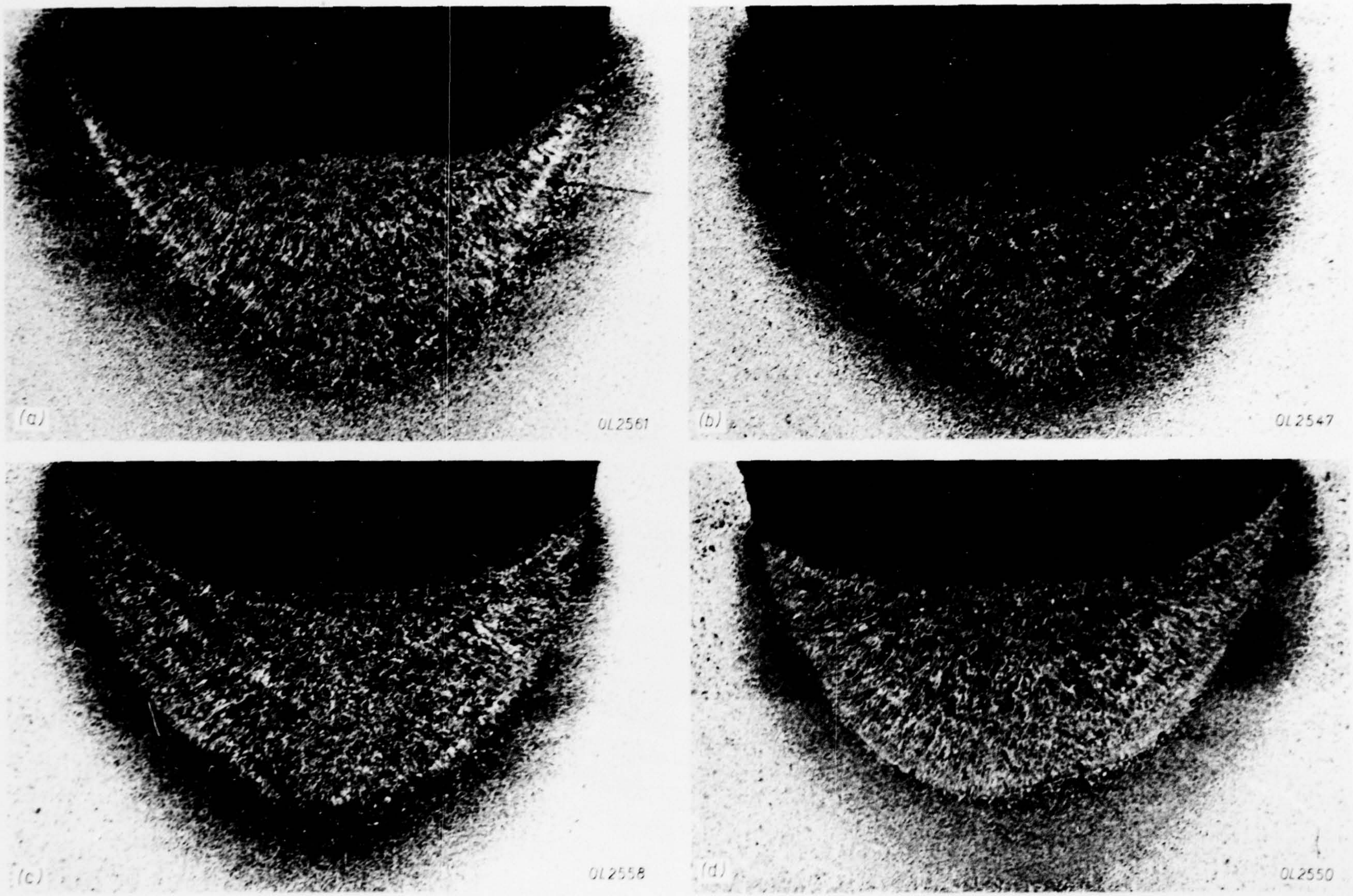


Fig.7. Bead in groove tests. Pulse 0.1sec, background x 8.25: a) 0.1; b) 0.2; c) 0.3; d) 0.4sec..

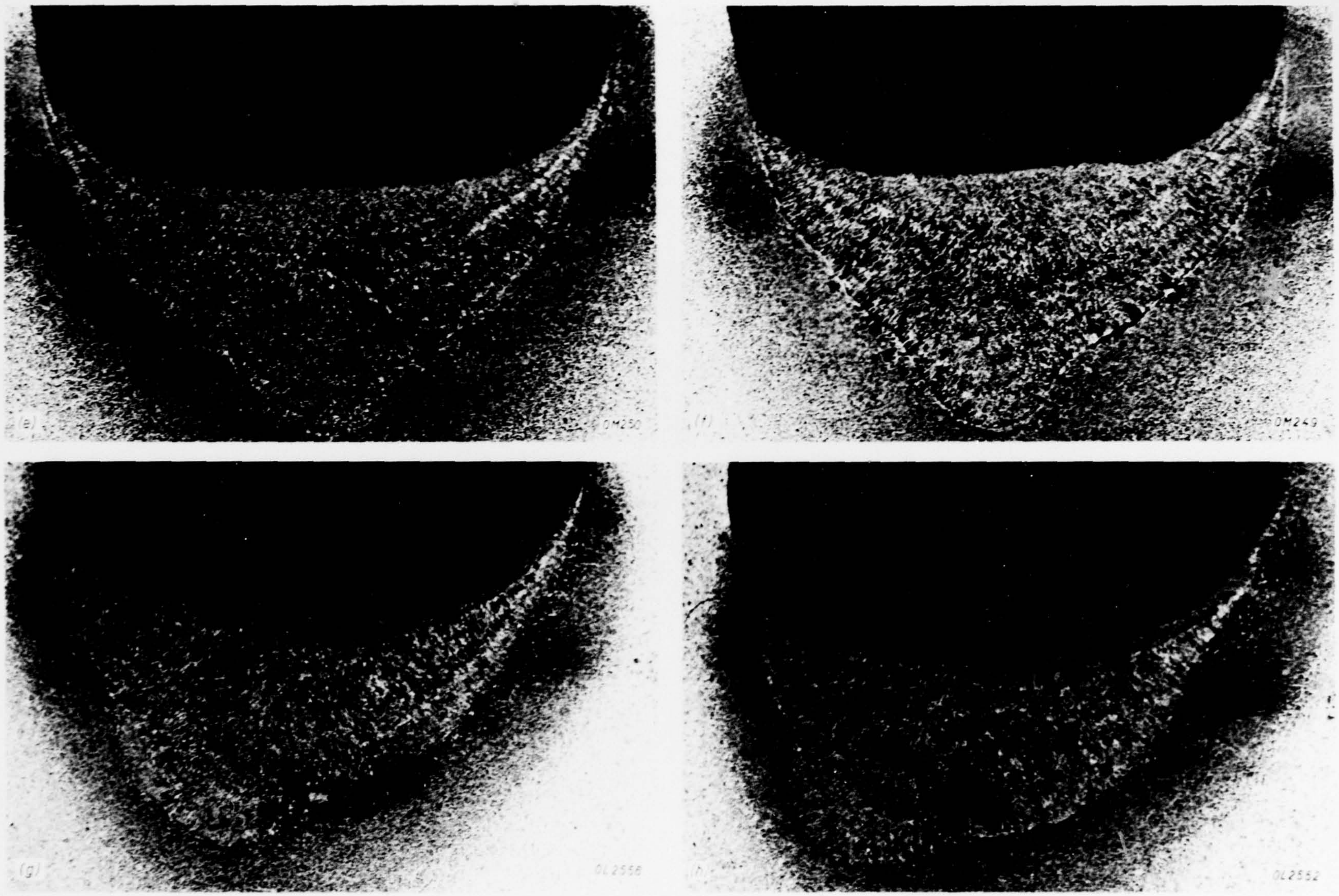


Fig.7. cont. Bead in groove tests. Pulse 0.2sec, background x 8.25: e) 0.1; f) 0.2; g) 0.3; h) 0.4sec.

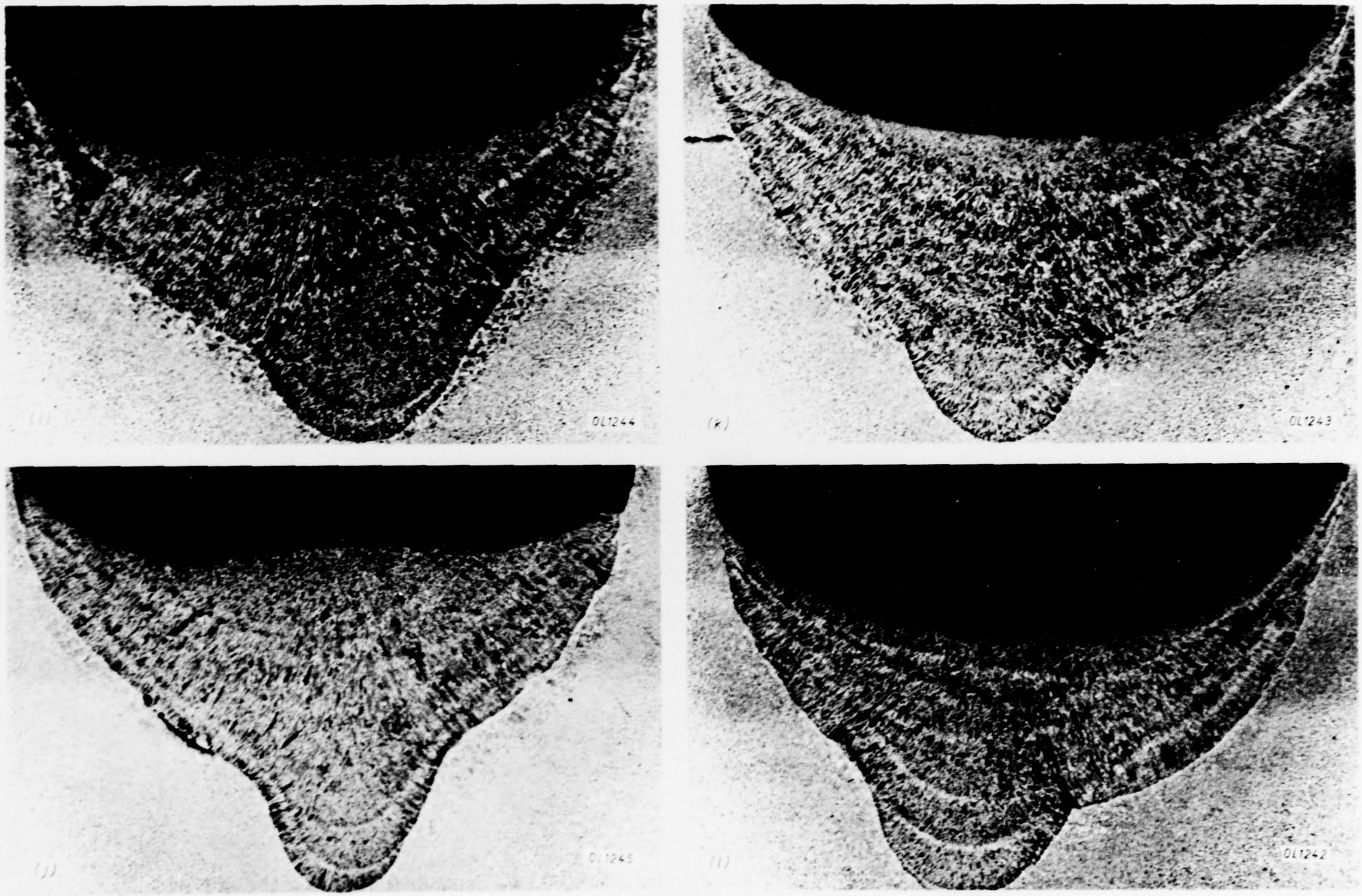


Fig.7. cont. Pulse time 0.3sec, background × 8.25: i) 0.1; j) 0.2; k) 0.3; l) 0.4sec.

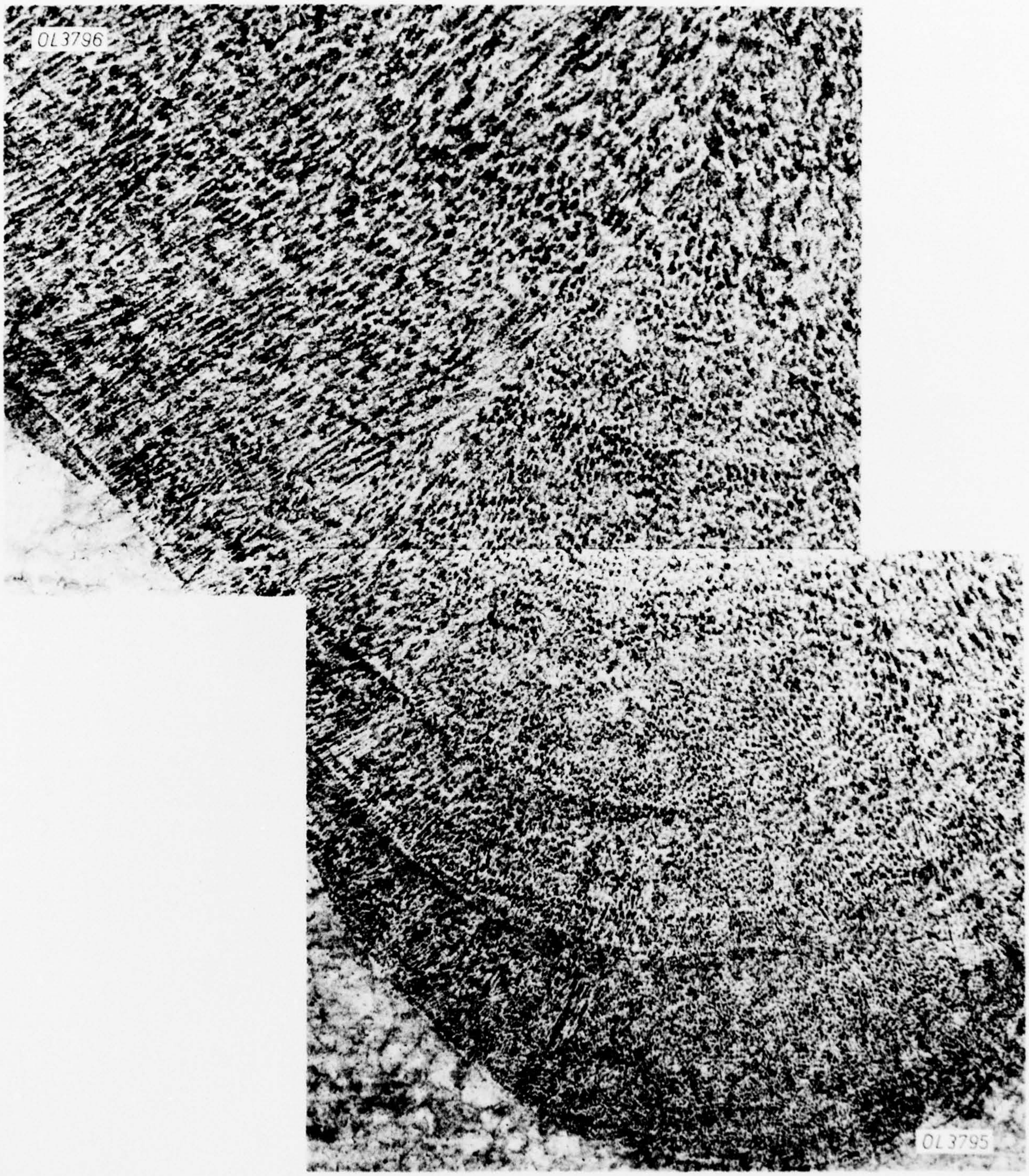
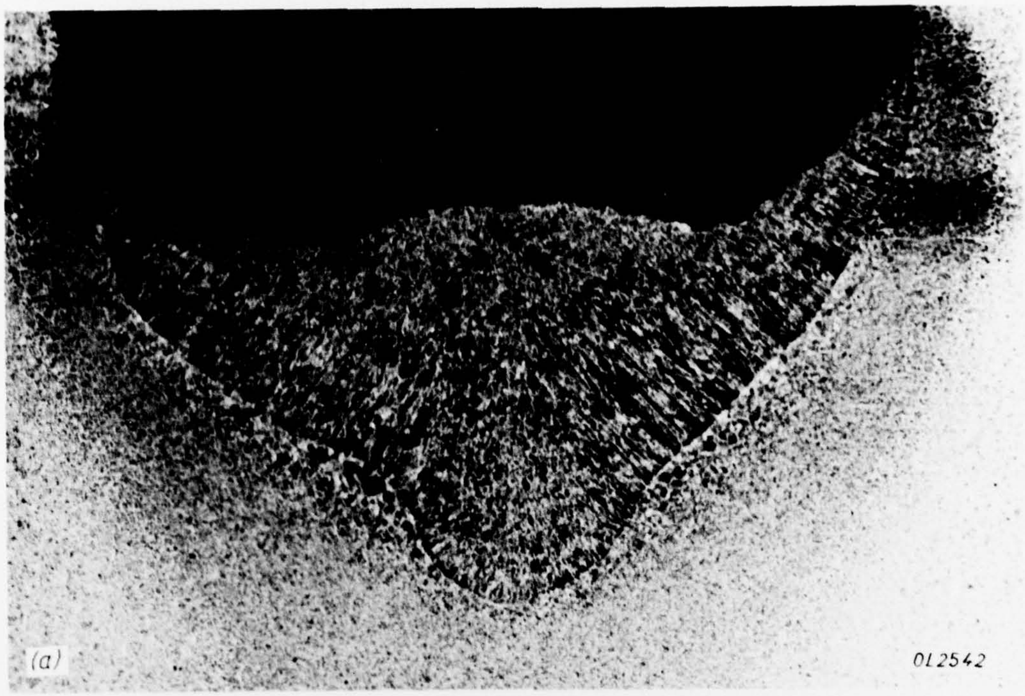


Fig.8. Bead in groove test-transverse section x 50. Pulse = 0.2sec, background = 0.2sec. Note progressive coarsening of structure away from weld root.



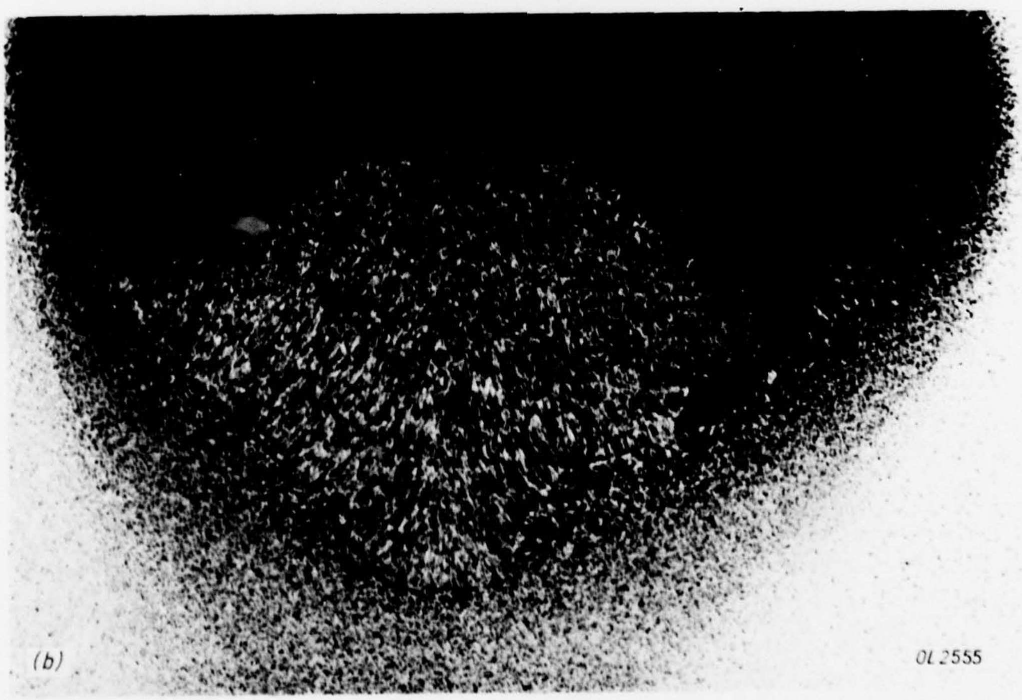
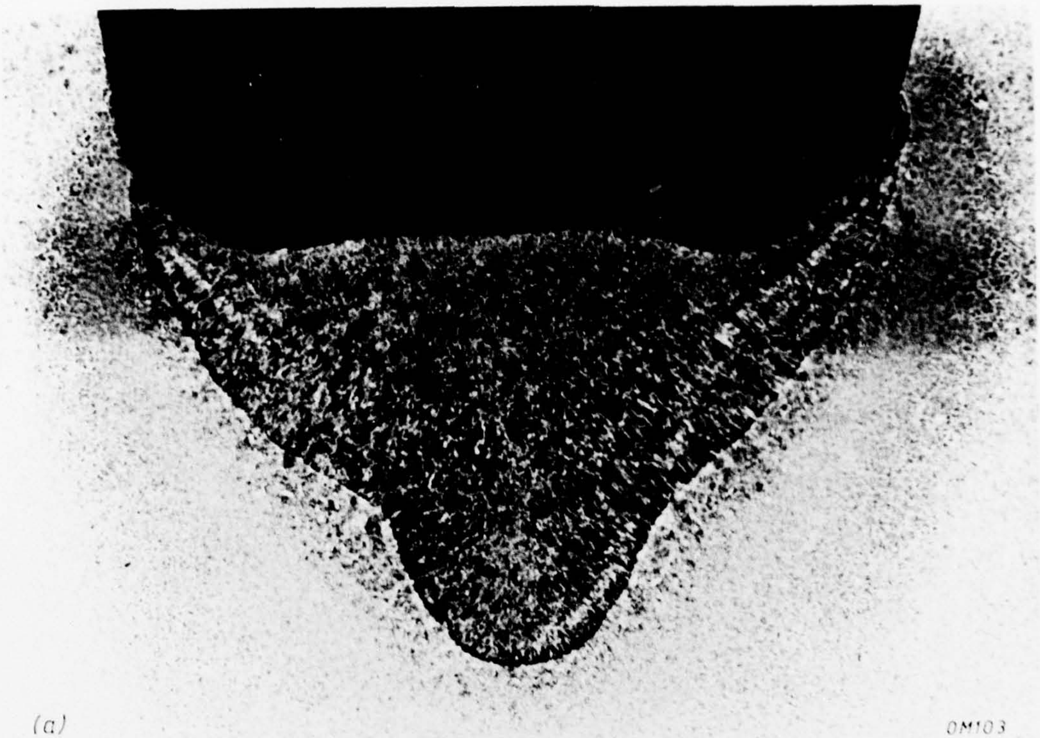


Fig.9. Effect of pulse current: a) 350A × 10; b) 400A × 10. Pulse conditions: Pulse 0.1sec, background 0.1sec. Compare with Fig.7 for 280A.



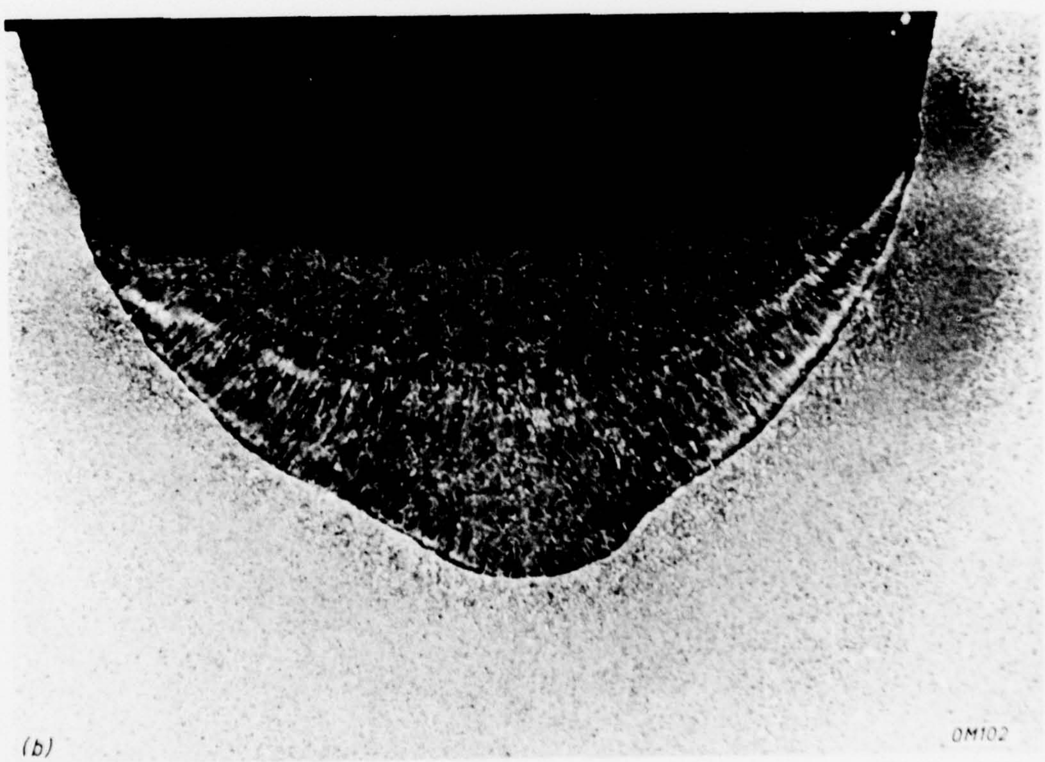


Fig.10. Effect of high frequency pulsing on weld shape: a) Pulse 0.05sec, background 0.05sec x 10 weld 288. b) pulse 0.025sec, background 0.025sec x 10, weld 285.

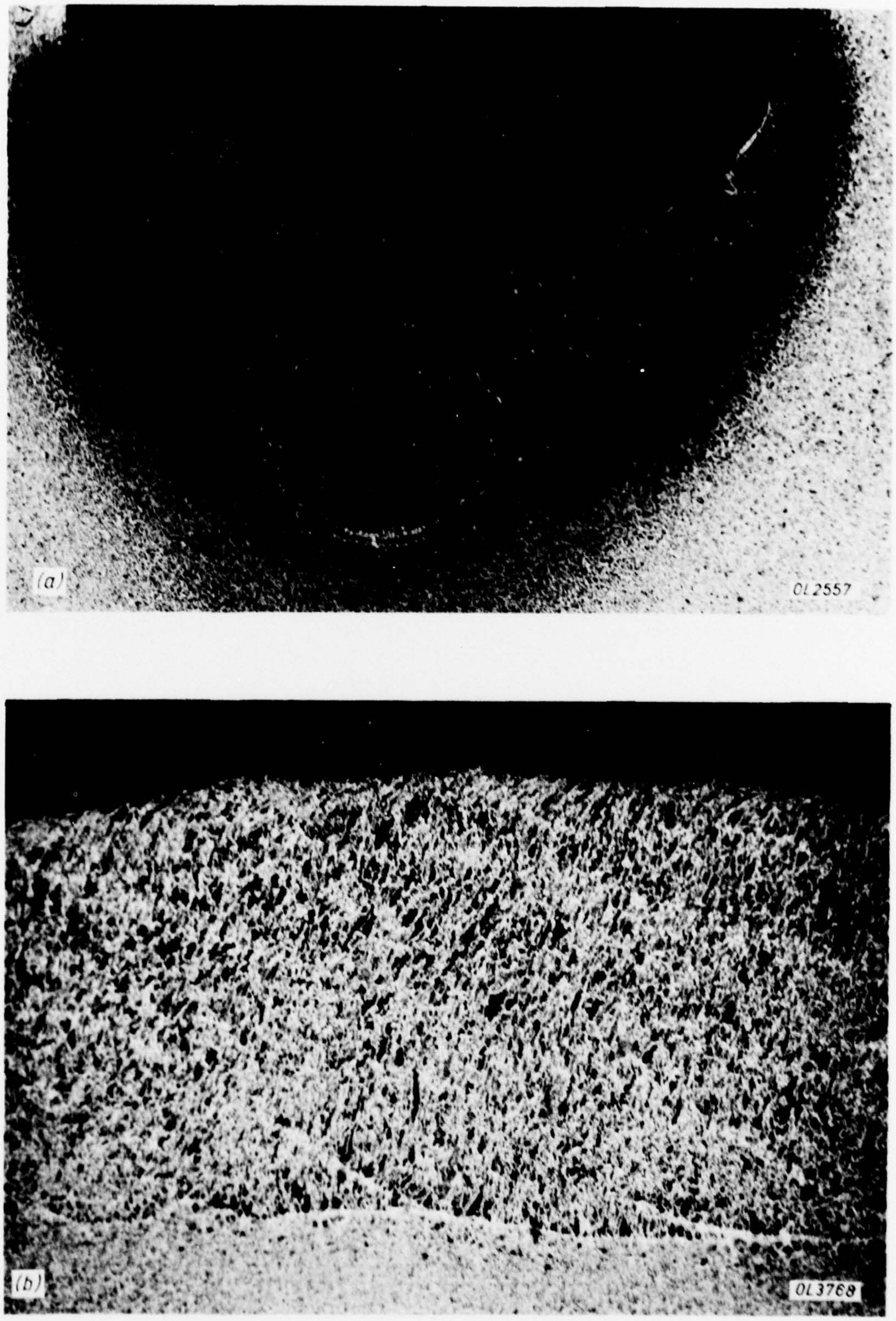


Fig.11. Low frequency pulsing, no modulation. Pulse 0.5sec, background 0.5sec: a) Transverse x 10, b) longitudinal x 16.

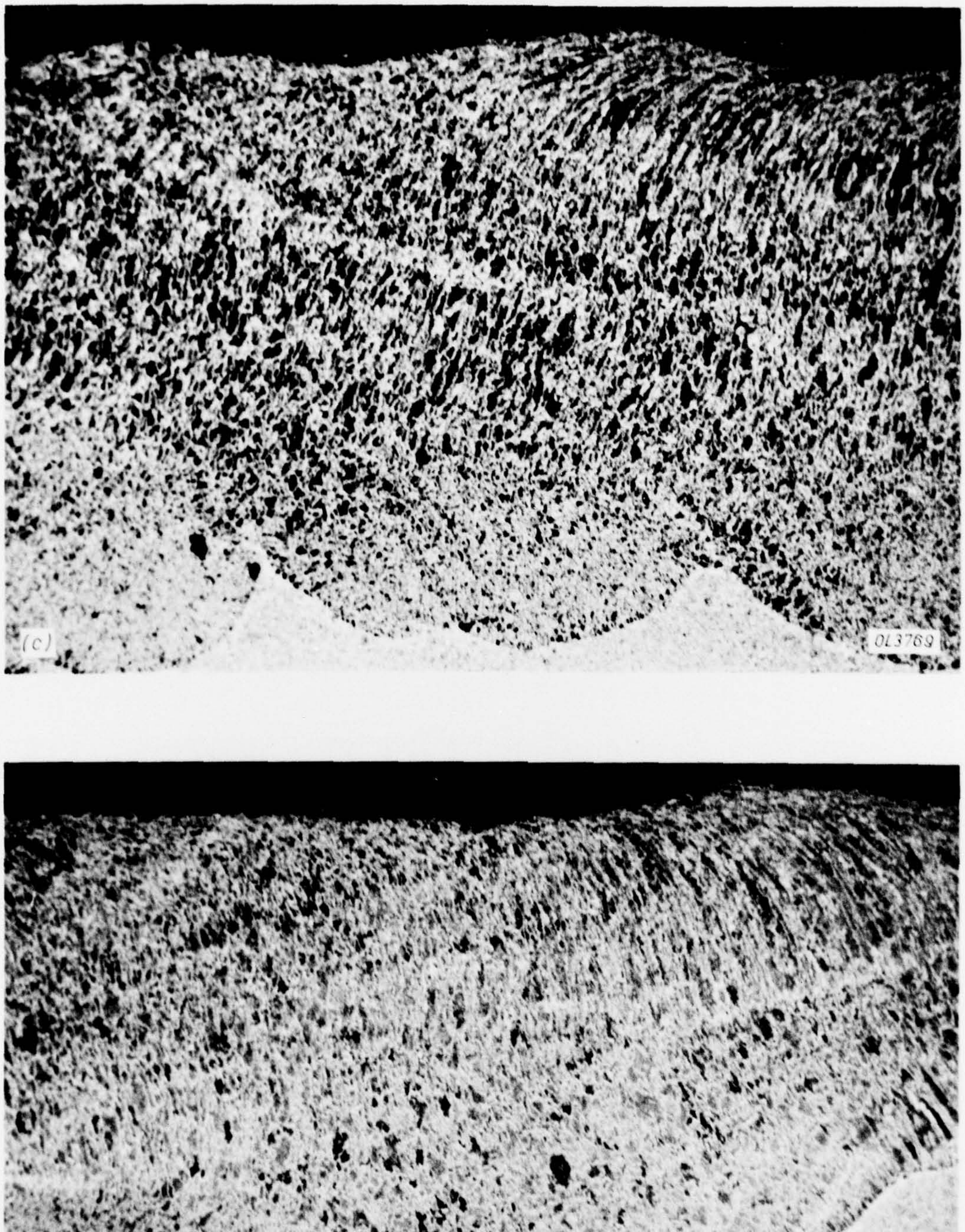


Fig.11. cont. c) Pulse 1sec, background 0.5sec x 16; d) pulse 2sec, background 0.5sec x 16.

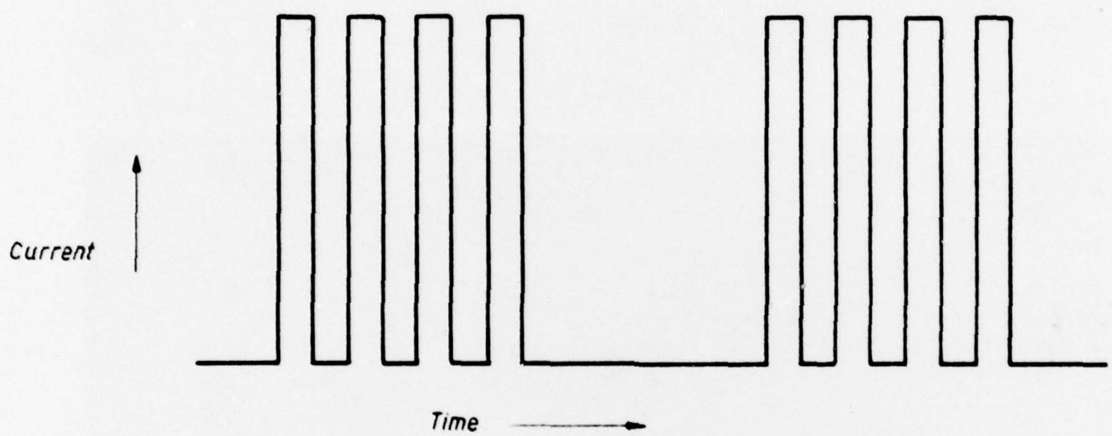


Fig.12. Diagrammatic representation of modulated current pulses.

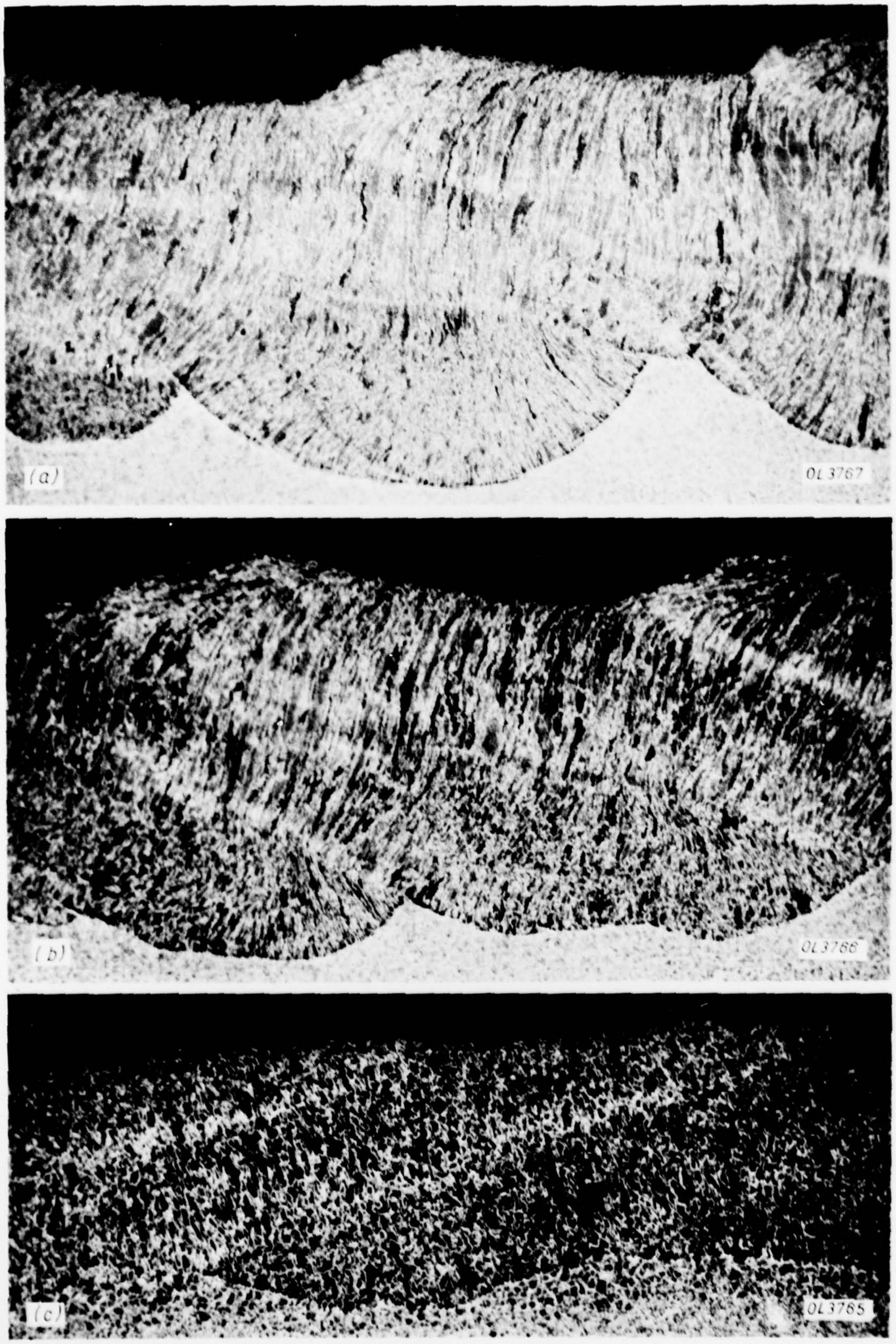


Fig. 13. Effect of current modulation superimposed onto 1sec pulse, 0.5sec background: a) 50Hz; b) 20Hz; c) 10Hz. x16

Fig.14. Effect of current modulation alone on weld pool shape x 8.5 a) 25Hz b) 50Hz c) 100Hz

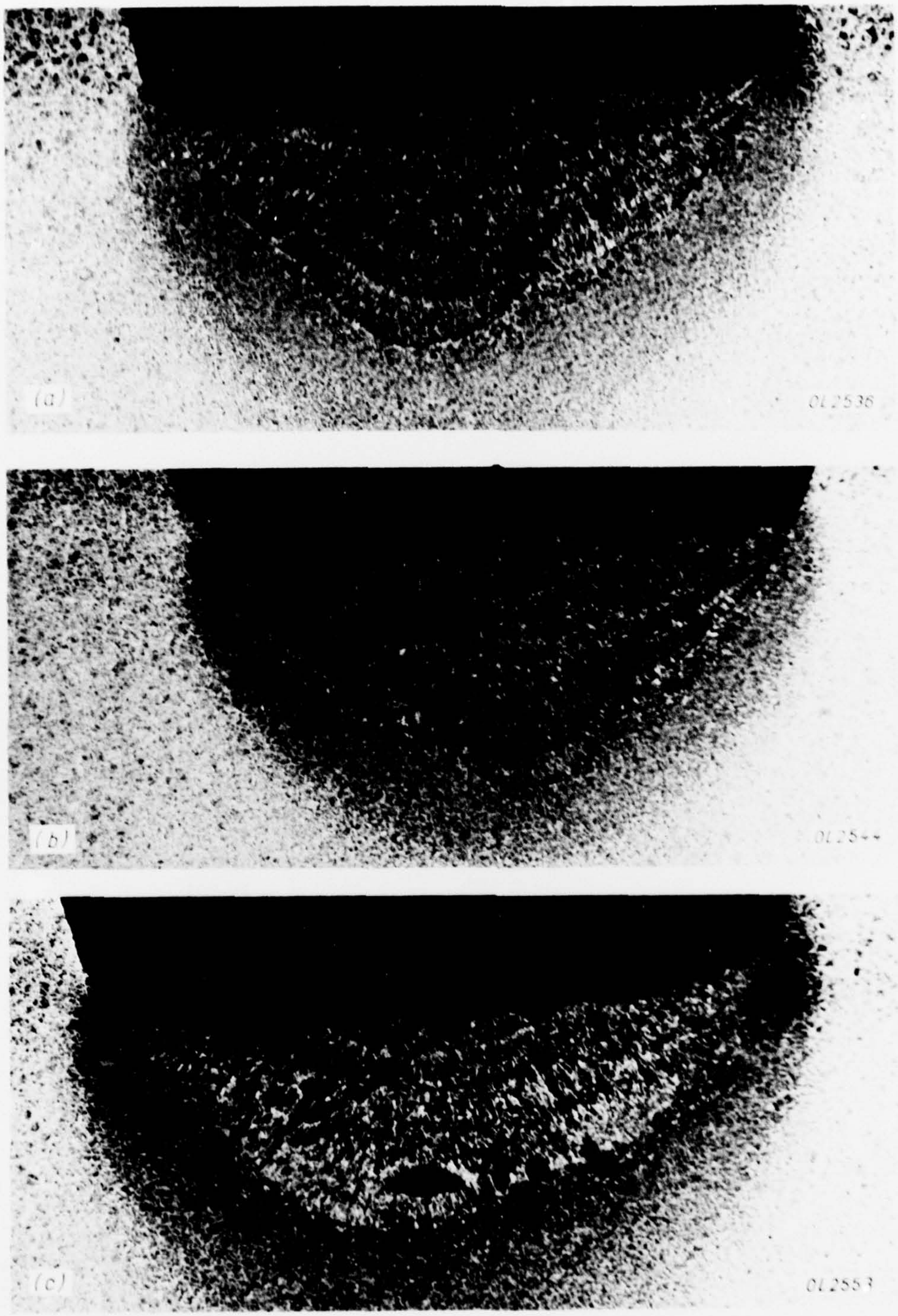


Fig.15. Effect of modulation frequency during current pulse on weld pool shape. Pulse 0.2sec, background 0.3sec, modulation: a) 50Hz; b) 25Hz; c) 10Hz.

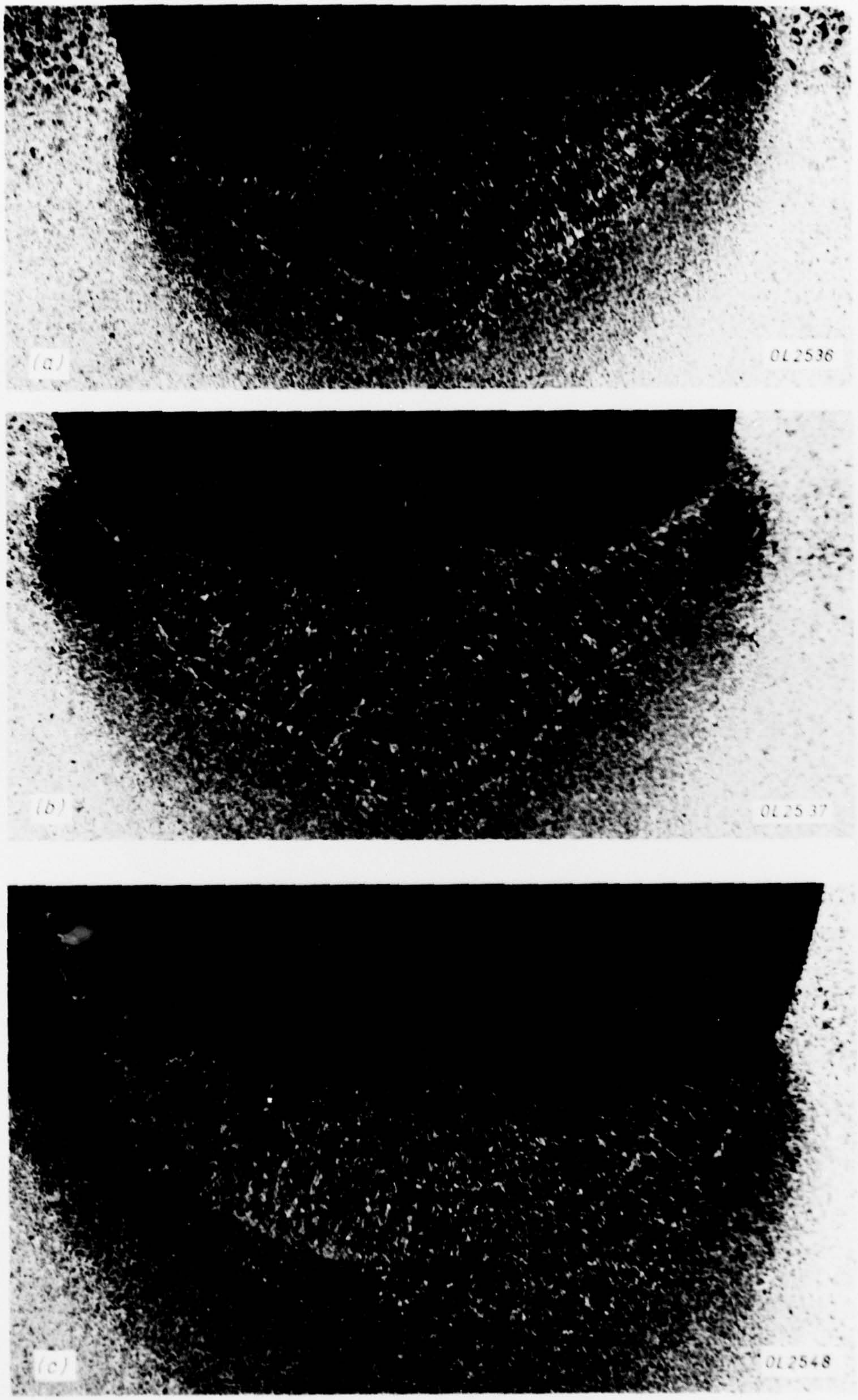


Fig.16. Effect of variation in modulation pulse/background ratio. Major pulse 0.2sec, background 0.3sec. Modulation pulse: a) 0.01sec, b) 0.02sec, c) 0.05sec. Background for a, b and c 0.01sec.